The Anthropic Principle and the Ikeda Threshold Rule

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Abstract
After a short digression into the anthropic principle I discuss the role of the Ikeda threshold state in relation to the famous Hoyle state in ^{12}C.

1 Introduction

There are certain postulates of which one does not quite know, whether they are utterly trivial or so deep, that one does not fully grasp their meaning. For me the Anthropic Principle is such a postulate. In the formulation of Barrow and Tipler [1] in their monograph "The Anthropic Cosmological Principle" the weak anthropic principle states

The observed values of all physical and cosmological quantities are not equally probable but they take on values restricted by the requirement that there exit sites where carbon-based life can evolve and by the requirement that the Universe be old enough for it to have already done so.

There also are the strong and the ultimate anthropic principle, but these are more speculative and I will not be dealing with them.

The anthropic principle was first introduced by Brandon Carter [2] on an symposium in celebration of the 500th birthday of Copernicus. It was thought as a word of caution that in contrast to the Copernican principle our sheer presence does place constraints on the world in which we live. Dicke [3] was one of the first to apply anthropic reasoning to an estimate of the age of the universe, which had to be at least 10^{10} years old to allow for the development of intelligent life. This estimate is based on the time needed for galaxy and star formation, the recycling of nuclear matter in stellar burning to form heavy elements prior to the formation of our solar system, and the development of life.

2 Fine tuning

The anthropic principle has its origin in the observation of the often spectacular "fine tuning" of the constants of nature deemed necessary for the existence of life. As Freeman Dyson stated [4]:

As we look out into the Universe and identify the many accidents of physics and astronomy that have worked together to our benefit, it almost seems as if the Universe must in some sense have known that we were coming.

The literature is full of examples of fine tuning, e.g. Refs. [1,5]. Martin Rees in his book "Just Six Numbers" [6] singles out $\mathcal{N}$ the ratio of the electrostatic to the gravitational force between electron and proton, ε a measure of the strong force, the density parameter $\Omega = \rho / \rho_c$, the cosmological constant Λ, Q a measure of the size of the fluctuations of the cosmic microwave background radiation, and the dimensionality of space. These six numbers are by no means complete, as they e.g. do not contain the strength of the weak interaction, respectively the mass of the vector bosons, which plays a crucial role in the big bang nucleosynthesis, the stellar burning and in super novae explosions. Max Born was the first to recognise that the atomic and molecular structures critically depend on the

* Dedicated to Professor Kiyomi Ikeda on the occasion of his 75th birthday.

Sommerfeld parameter α and the electron to proton mass ratio $\beta = m_e / m_p$. The allowed regions in the landscape of β versus α are shown by Tegmark [7].

Tegmark [7] also presented the constraints on the strong α_s and the electromagnetic coupling constant α as shown in fig. 1. The observed values of α_s and α are presented by the black square. Below the horizontal line the deuteron is unbound, whereas the dark grey area shows the region, in which the diproton is bound, the so-called diproton disaster. With the deuteron unbound, the formation of heavier elements would become impossible, and the universe would consists of hydrogen only. Similarly with the diproton bound, no hydrogen would have survived the big bang. The figure shows most impressively the extremely narrow window in the strong coupling constant in which the formation of heavier elements and thus also carbon is possible. Also shown in the figure the region in which carbon is stable, and the region, in which there are no nonrelativistic atoms.

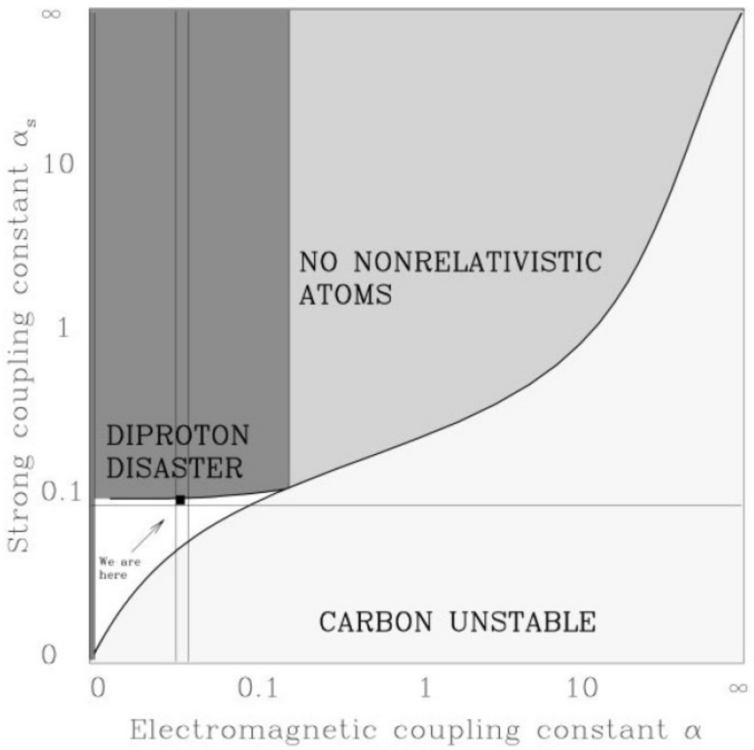

Fig. 1: Landscape of (α_s, α) from Ref. [7]. For an explanation see text.

The notion of "fine tuning" clearly introduces an element of subjectivity.

3 The multiverse as an explanation of fine tuning

The observation of the "fine tuning" of the constants of nature quite naturally has been seen as an indication for intelligent design, e.g. Ref. [5]. In the absence of a "theory of everything", that uniquely predicts all constants of nature, one is alternatively led to the idea of a multiverse of an infinite number of parallel universes, every one with its own constants of nature randomly "picked", but obeying the same physical laws, e.g. Ref. [8]. In the words of Tegmark

Either God fine-tuned the Universe for us to be here, or there are many universes, each with different values of the fundamental constants, and not surprisingly we find ourselves in one in which the constants have the right values to permit galaxies, stars and life.

Interestingly Leibniz [9] already thought about the possibility of an infinite number of possible world, of which ours is the best.

Und wenn man auch alle Zeiten und alle Orte ausfüllen würde, so bleibt es doch dabei, dass man sie auf unendlich viele andere Arten hätte ausfüllen können; es bleibt dabei, dass es eine ***Unendlichkeit von möglichen Welten*** *gibt, aus der Gott notwendig die beste ausgewählt haben muss, denn er tut nichts, ohne dass er der höchsten Vernunft gemäß handelt.*

I was quite proud to have discovered this quotation only to find out, that Barrow and Tipler [1] already refer to it in their book.

4 The Hoyle state and the Ikeda threshold rule

One of the most celebrated cases of "fine tuning" is the Hoyle state in the triple alpha stellar burning leading to ^{12}C. The burning process proceeds in two steps. First the unbound ground state of ^{8}Be with a mean life of 5.10^{-17} s is formed in the collision of two alpha particles, and then ^{8}Be fuses with an alpha particle in a subsequent collision to form ^{12}C. For this second process to take place with a sufficient probability Hoyle [10] predicted the existence of a $J^\pi = 0^+$ resonance in ^{12}C at ≈ 7.68 MeV near the threshold for 3α decay at 7.275 MeV. The famous Hoyle state was soon found at $E_x = 7.654$ MeV with the predicted spin and parity.

There is much folklore around the Hoyle state. Hoyle himself is quoted as having said that *"Nothing has shaken my atheism as much as this discovery"* . The Hoyle state is the more spectacular as shell model calculations notoriously fail to predict it [10]. In fig. 2 recent results of no core shell model calculations [11] for ^{12}C with (+3NF) and without the inclusion of a three body force are shown. Whereas the excitation energies of the other states are reasonably reproduced, the 0^+ Hoyle state is 5-6 MeV too high.

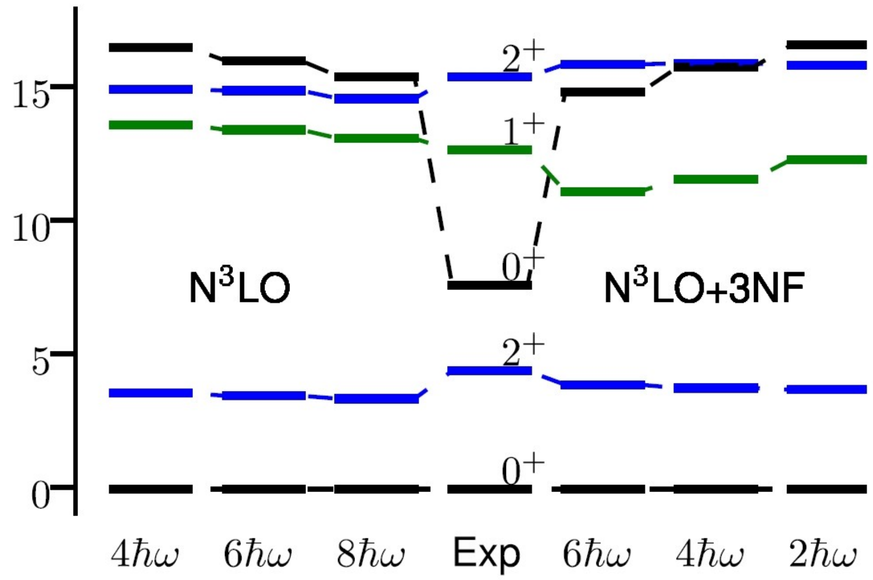

Fig. 2: No core shell model calculations of states in ^{12}C performed with (right) and without (left) the inclusion of a three body force, Ref. [12] .

The Hoyle state in contrast follows naturally from the clustering near the breakup threshold as predicted by the Ikeda threshold rule [13] which followed from the observation of rotational bands with diatomic molecule like structure near threshold, and which since has been extensively confirmed [14] :

"Diatomic molecule-like structures in the self-conjugate 4n light nuclei appear systematically at near the threshold energy for the decay into the relevant subunit nuclei"

Of course this threshold rule does not predict the exact location of these threshold states, and there consequently remains some fine tuning. But the occurrence of these threshold states is a direct consequence of the clustering near threshold as predicted by the Ikeda rule. It has therefore surprised me, that in all the discussions of the anthropic consequences of the Hoyle state the Ikeda threshold rule has never been mentioned.

It is to this threshold behaviour of the Ikeda rule that we owe our existence, and it thus seems only fitting to thank Professor Ikeda for this on the occasion of his 75th birthday.

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